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Reservoir simulation study of CO_2 storage in formations containing both aquifers and coal seams

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Abstract

Geological storage of CO_2 is a viable option for the mitigation of greenhouse gas emissions. Formations such as saline aquifers and coal seams have distinct storage mechanisms; in saline aquifers, the CO_2 is mainly stored by compression and/or dissolution in the formation fluid, whereas in coal seams, the CO_2 is primarily stored by adsorption. To investigate the impact of CO_2 dissolution in formation fluid on CO_2 storage in coal and enhanced coalbed methane production, two scenarios are considered (1) CO_2 injection and coalbed methane production for a single coal seam, (2) CO_2 injection in two coal seams with an aquifer in-between while coalbed methane is produced in the upper coal seam. It is found that although CO_2 dissolution in formation water is not the main storage mechanism in coal reservoirs, including CO_2 dissolution can lead to significant differences in the simulation results. In addition, including CO_2 dissolution leads to more accurate description of the ECBM process through more accurate prediction of water saturation and thus the gas effective permeability, the overall reservoir pressure and gas flow response to CO_2 injection. The results also suggest that for CO_2 storage in lower rank coals, which usually have higher porosity and permeability, CO_2 dissolution in the formation water should be considered in order to more accurately describe the CO_2 storage and ECBM behaviour. The results also show that water containing formations in between the coal seams, although often low in porosity and thus insignificant in overall CO_2 storage capacity, also have a significant impact on the overall CO_2 storage and enhanced coalbed methane recovery behaviours when considering CO_2 dissolution modelling in formation waters.

Keywords: ECBM; CO_2 dissolution; coal swelling; relative permeability

1. Introduction

Geological storage of CO_2 is a viable option for the mitigation of greenhouse gas emissions. Two main reservoir types exist; porous formations such as saline aquifers or depleted oil or gas reservoirs and, of lesser importance in terms of storage capacity, coal or shale reservoirs. These reservoirs have distinct storage mechanisms; in the porous formations the CO_2 is mainly stored within the porosity by compression and/or dissolution in the formation fluid, whereas in coal seams, the CO_2 is primarily stored by adsorption. Geological storage scenarios exist where these two reservoir types could be present within a geological sequence and come into contact with migrating CO_2. For

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instance, coal seams within the overburden for CO_2 storage in aquifers and the presence of other water containing formations in-between coal seams targeted for CO_2 storage-enhanced coalbed methane recovery.

Reservoir simulators, such as TOUGH2, have been used for CO_2 storage in saline aquifers and oil and gas reservoirs [1,2]. However at present these do not represent the adsorption process key to explaining gas storage and migration in coal seams. On the other hand, the existing coal seam gas reservoir simulators allow us to simulate CO_2 storage in coal seams [3], but do not include the dissolution of CO_2 in formation waters that is a key process for representing long term storage in aquifers. Incorporating these processes into one simulator would allow an integrated approach to problems that involve both aquifers and coal seams or other gas adsorbing formations. For example, it would allow the impact to be investigated of coal seams within the overburden with CO_2 storage in aquifers or where CO_2 is stored in formations which comprise sequences of aquifers and adsorbing geology such as coals and gas shales. It would also allow the impact to be investigated of CO_2 dissolution in formation water of the coal seams and adjacent water bearing formations on CO_2 storage in coal and enhanced coalbed methane recovery.

In order to simulate this situation models are required which represent the mechanisms operating for both reservoir types. Pan and Connell [4] have further developed the coal seam gas reservoir simulator, SIMED II, to include CO_2 dissolution in formation waters and a more accurate Equation of State, the Span and Wagner model [5], to describe CO_2 density. The modifications to SIMED II were tested through a code comparison study with TOUGH2 for CO_2 storage in a saline aquifer, using the Sleipner Vest case study in the Norwegian sector of the North Sea presented by Pruess et al. [6]. This involves CO_2 migration in the Utsira formation with 10,000 tonnes of CO_2 injected in a 1 metre section of a horizontal well over a 2-year period. The code comparison results show that the modified SIMED II model and TOUGH2 model are in close agreement with respect to the CO_2 phase distribution as well as spatial distribution of injected CO_2. Pan and Connell [4] also present reservoir simulation cases that investigate the impact of the presence of coal seams as a layer in the overburden on vertical CO_2 migration after storage in a saline aquifer. In addition simulations are used to investigate the key aquifer and coal seam properties which affect the CO_2 storage and migration behaviour in formations where coal seams are interlayers for CO_2 storage in aquifers. It was found that coal seams can have a significant impact on CO_2 storage and migration behaviour by providing extra storage capacity and influencing the CO_2 flow path both vertically and horizontally. The potential impact of coal seams in these scenarios is related to a range of factors but key ones are the adsorption capacity and the permeability. The results also indicate that coal seam permeability decrease due to CO_2 adsorption induced coal swelling, although regarded as a technical obstacle to CO_2 injection in the deep unminable coal seams would further influence the CO_2 flow path, helping to reduce the upward CO_2 flow due to buoyancy and pressure. This could act to reduce CO_2 contact with cap rocks and lower the risk of CO_2 leakage.

In the scenarios considered by Pan and Connell [4] CO_2 was injected into aquifers and then migrated into contact with coal seams. In this current paper the model developed by Pan and Connell [4] is used to investigate the impact of CO_2 dissolution in formation water on CO_2 storage in coal seams and enhanced coalbed methane recovery.

2. Case studies

To investigate the role of CO_2 dissolution on the simulation of CO_2 storage in coal seams and enhanced coalbed methane recovery, two scenarios are considered in this work. These scenarios are constructed to investigate likely practical situations for CO_2 injection in coal and the results are compared with the equivalent simulation where CO_2 dissolution in the formation waters is not represented. In the first scenario, CO_2 storage to enhance coalbed methane recovery in a single coal seam is considered. For this scenario injected CO_2 displaces adsorbed methane and enhances coalbed methane recovery from a production well. In the second scenario two coal layers separated by a water bearing formation (aquifer) is considered. In this scenario, CO_2 is injected into both coal seams, of which the upper seam is CH_4 rich and the lower seam is without CH_4. A production well is completed in the upper coal seam to produce coalbed methane. The lower coal seam which has a low CH_4 content and thus has a low value for CBM or ECBM, but would add to the CO_2 storage capacity.

The layout of Scenarios 1 and 2 are presented in Figures 1 and 2, respectively. In Scenario 1, the reservoir is composed of a coal seam of 3 metres thickness. The injection well is located in a corner of the considered area and the production is located in the opposite corner. The grid system is 20 by 20 blocks in the horizontal directions and 1 in the vertical direction. In Scenario 2, the reservoir is composed of a lower coal seam of 3 metres thickness, a middle water bearing formation or aquifer of 9 metres thickness and an upper coal seam of 3 metres thickness. The injection well is also located in a corner and is completed in the two coal seams only. The production well, which is located in the opposite corner, is completed in the upper coal seam only. The grid system for Scenario 2 is 20 by 20 by 5. For both scenarios, each grid in the x and y direction is 10 metres.

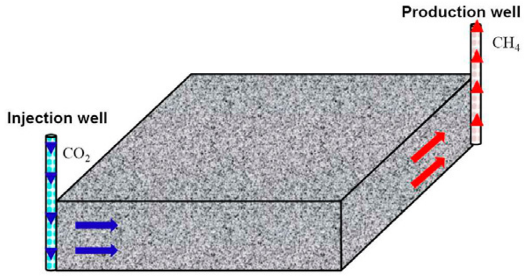

Figure 1. Layout for Scenario 1

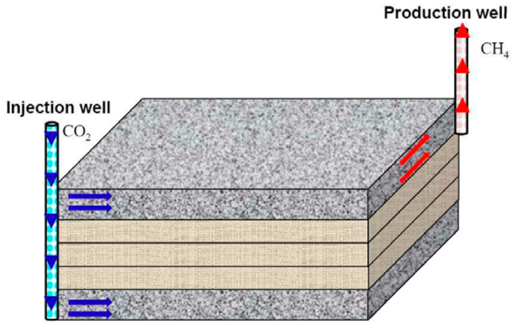

Figure 2. Layout for Scenario 2

Different case studies are performed for each scenario to investigate the impact of representing CO_2 dissolution on the simulation of CO_2 storage in coal and enhanced coalbed methane recovery and to identify situations where CO_2 dissolution modeling is essential to more accurately describe the CO_2 storage and ECBM process. For Scenario 1, analyses are made for different coal reservoir properties, such as depth, initial permeability, relative permeability, porosity, adsorption capacity, initial gas content, and swelling. These are key properties in CBM and ECBM processes. For Scenario 2, the rock properties of the water containing formation in-between the two coal layers are investigated with respect to the overall CO_2 storage and ECBM process with and without CO_2 dissolution. Analyses are made for rock porosity, permeability, relative permeability. The rock properties for the coal seams are fixed for all the cases in Scenario 2 to simplify the analyses since the impact of coal properties on modeling results are investigated in Scenario 1.

The Shi and Durucan [7] model is used to define the behaviour of the coal seam permeability as CO_2 adsorbs to the coal. The Shi and Durucan model describes the coal permeability change from a stress approach:

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}\left(P - P_0\right) + \frac{E\varepsilon_V}{3\left(1-\nu\right)} \tag{1}$$

where σ is the effective horizontal stress, σ_0 is the effective horizontal stress at the initial reservoir pressure, ε_V is the volumetric swelling/shrinkage strain, P is pore pressure, E is Young's Modulus and ν is Poisson's ratio. To relate the permeability with effective stress, the equation below is used:

$$k = k_0 e^{-3c_f(\sigma-\sigma_0)} \tag{2}$$

where c_f is referred to as the cleat volume compressibility with respect to changes in the effective horizontal stress normal to the cleats [7].

For Scenario 1, eight cases are constructed to evaluate the impact of coal properties on representing CO_2 dissolution in the modeling. For case 1, the key parameters are listed in Table 1. The relative permeability for Case 1 is Curve 1 as shown in Figure 3. Other important reservoir parameters including the Shi and Durucan model parameters, Langmuir pressure, P_L, Desorption time, t_d, are summarised in Table 2.

Table 1. Key reservoir properties for Scenario 1

	Depth (m)	k (md)	Rel Perm	ϕ (%)	C_0 (m^3/t)	V_{L, CO_2} (m^3/t)	ε_V (%)	Injection well control	Well type
Case 1	900	5.0	Curve 1	1%	12.0	35.4	2.5	BHP=15MPa	Vertical

The other seven cases are constructed with only 1 parameter varying from those used for Case 1 in order to evaluate the sensitivity of each parameter on the simulations with and without CO_2 dissolution. For Case 2, all parameters are the same as Case 1 except that the depth is at 1200m. Whereas, for Case 3, the reservoir permeability is different from that used for Case 1, that is 1.0 md. For Case 4, all parameters are the same as that in Case 1 except that the relative permeability is Curve 2 as shown in Figure 4. For Case 5, all parameters are the same as that in Case

1 except that the cleat porosity, ϕ, is 2%. For Case 6, all parameters are the same as that in Case 1 except that the initial gas content, C_0, is 6 m^3/t. For Case 7, all parameters are the same as that in Case 1 except that the Langmuir volume for CO_2, $V_{L,CO2}$, is 45.4 m^3/t. For Case 8, all parameters are the same as that in Case 1 except that the coal swelling ratio, ε_V, is 3.5%.

Table 2. Other important properties for Scenario 1

$V_{L,CH4}$ (m^3/t)	$P_{L,CH4}$ (MPa)	$t_{d,CH4}$ (days)	$V_{L,CO2}$ (m^3/t)	$P_{L,CO2}$ (MPa)	$t_{d,CO2}$ (days)	c_f (MPa^{-1})	E (GPa)	ν	Production well
27.3	4.0	10.	35.4	1.6	5.0	0.019	3.0	0.35	BHP=345 kPa

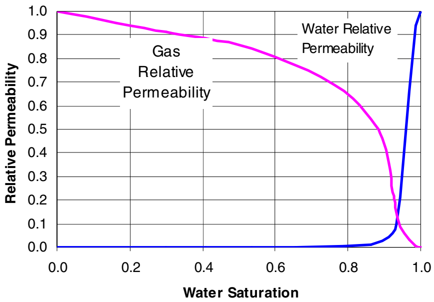

Figure 3 Relative permeability curve 1

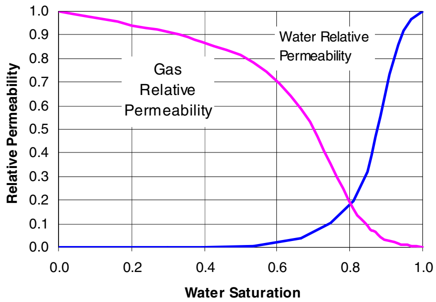

Figure 4. Relative permeability curve 2

For Scenario 2, five cases are constructed to evaluate the impact of the interlayer aquifer on the simulations with and without CO_2 dissolution, including the water in the coal seams. For Case 1, the key parameters for the aquifer are listed in Table 3. The upper coal seam has the same properties as in Case 1 of Scenario 1 and the lower coal seam has the same properties as in Case 3 of Scenario 1. The vertical permeability is 1 tenth of that in the x and y directions for all formations.

Table 3. Other important properties

	ϕ (%)	Thickness (m)	*k* (md)	Rel perm
Case 1	1.0	9.0	0.5	Curve 1

For Case 2, all parameters are the same as those in Case 1 except that the porosity is 2%. For Case 3, all parameters are the same as those in Case 1 except that the total thickness of the aquifer is 27 m. For Case 4, all parameters are the same as those in Case 1 except that the aquifer permeability is 0.05 md. For Case 5, all parameters are the same as those in Case 1 except that the relative permeability is Curve 2.

It should be noted that rock properties may be correlated, for example, porosity and permeability. In this work, they are treated as independent to better indentify its sensitivity.

3. Results and discussions

3.1 Scenario 1

The key simulation results used to evaluate the CO_2 storage and ECBM behaviour include the CO_2 breakthrough time (t_b), total CO_2 injected at breakthrough time ($V_{t,CO2}$), peak CH_4 production rate (Q_{CH4}) and total CH_4 recovered ($V_{t,CH4}$). The results for those parameters for the cases in Scenario 1 are summarised in Table 4. Comparisons are made between the models with and without accounting for CO_2 dissolution in the formation water. The rates here are 1 quarter of the total rates for the vertical wells and half of the total rate for the horizontal wells.

For Case 1, the peak methane production rate is 2130 m^3/day when CO_2 dissolution in the formation water is included in the modeling and 2270 m^3/day without. The peak rate difference is about 6.6%. The CO_2 breakthrough time is 834 days with CO_2 dissolution in formation water and 805 days without. The difference for the breakthrough times is about 3.6%. When the CO_2 composition in the produced gas reaches 3% it is considered that CO_2

breakthrough has occurred, as it is assumed that the produced gas has to meet a specification of 97% methane. The total CH_4 produced at CO_2 breakthrough is 1.32 million m^3 with CO_2 dissolution compared to 1.36 million m^3 without; a difference of 3%. The total CO_2 injected up to CO_2 breakthrough time is 3.71 million m^3 with CO_2 dissolution and 3.68 million m^3 without. This is a difference of about 0.8%. This is comparable to the total CO_2 dissolved in the formation water, which is about 0.5% of the total CO_2 injected. These differences are caused by the different water saturation between the two models, leading to different gas effective permeabilities and thus diverging reservoir pressures and flow behaviour. Case 1 is provided as a base case. One parameter change is made for the subsequent cases to evaluate the sensitivity of that parameter for the different modeling on the overall ECBM process.

Table 4. Simulation results for Scenario 1

	Q_{CH4} (m^3/day)	t_b (days)	$V_{t,CH4}$ (10^6 m^3)	$V_{t,CO2}$ (10^6 m^3)	Q_{CH4} (m^3/day)	t_b (days)	$V_{t,CH4}$ (10^6 m^3)	$V_{t,CO2}$ (10^6 m^3)
	With CO_2 dissolution				Without CO_2 dissolution			
Case 1	2130	834	1.32	3.71	2270	805	1.36	3.68
Case 2	1950	934	1.35	3.77	2080	895	1.37	3.72
Case 3	437	4940	1.56	4.30	470	4722	1.61	4.23
Case 4	2620	819	1.44	4.06	2720	803	1.46	4.02
Case 5	1880	940	1.24	3.70	2140	862	1.30	3.61
Case 6	1270	1069	0.53	4.05	1320	1035	0.55	4.00
Case 7	1610	1247	1.61	5.22	1670	1209	1.63	5.15
Case 8	1510	1229	1.51	3.90	1600	1191	1.53	3.85

For Case 2, a deeper depth of 1200 metre is considered in the simulation compared with 900 metre depth in Case 1. The rest of the parameters are same as in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 6.7%, 4.4%, 1.5% and 1.3%, respectively. Compared with Case 1, depth only has a slight further impact on the modeling difference between using and not using CO_2 dissolution.

For Case 3, the reservoir permeability is 1 md compared to 5 md in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 7.4%, 4.6%, 3.2% and 1.7%, respectively. Compared with Case 1, permeability has a slight further impact on the difference between using the two modeling methods.

For Case 4, the relative permeability is Curve 2 as shown in Figure 4. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 3.8%, 2.0%, 1.4% and 1.0%, respectively. These results mean that if the coal relative permeability follows Curve 2, using or not using CO_2 dissolution yield small differences. Compared with Case 1, it shows that relative permeability has a strong impact on the difference between using the two modeling methods.

For Case 5, the cleat porosity is 2% compared with 1% in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 13.8%, 9.0%, 4.8% and 2.5%, respectively. The large difference is due to the amount of CO_2 dissolved in the formation water is significantly increased from the conditions as in Case 1. About 1.05% of injected CO_2 is dissolved in formation water at CO_2 breakthrough time. Thus gas saturation in the cleat is much lower than that when not accounting for CO_2 dissolution. This alters the gas effective permeability and overall pressure and flow response in the reservoir. Compared with Case 1, porosity has a huge impact on the difference between using the two modeling methods.

For Case 6, the initial CH_4 content is 6 m^3/t compared with 12 m^3/t in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 3.9%, 3.3%, 3.8% and 1.3%, respectively. Compared with Case 1, the initial CH_4 content has a significant impact between the two different modeling methods. Because desorbed CH_4 will enter the coal cleat and alter the CO_2 partial pressure, which determines the amount of CO_2 dissolved in the formation water. This in turn changes the water saturation and then the gas effective permeability and overall reservoir pressure and gas flow behaviour.

For Case 7, the coal has a higher CO_2 storage capacity than that in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are

3.7%, 3.1%, 1.2% and 1.4%, respectively. The results suggested that with higher CO_2 storage capacity, using the two different methods yield closer results, which means that without using CO_2 dissolution can still be representing the real behaviour.

For Case 8, the coal has a high swelling ratio then that in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 6.0%, 3.2%, 1.3% and 1.3%, respectively. Compared with Case 1, swelling ratio has a moderate further impact on the difference between using the two modeling methods.

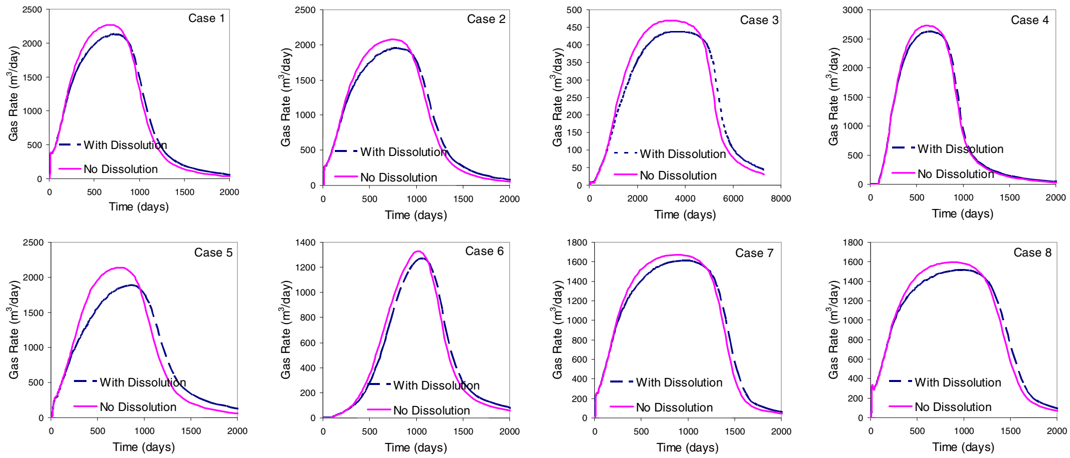

Figure 5. Comparison of CH_4 production rate for different cases in Scenario 1

Figure 5 presents the CH_4 production rate for the various cases. It can be seen that the rates differ significantly in Cases such as Cases 1, 3 and 5; and the rates are quite similar in Cases such as 4, 6 and 7. Hence, for ECBM through CO_2 storage in low rank coals, which are usually water saturated and have higher porosity, a relative permeability curve close to Curve 1, and low adsorption capacity, to include CO_2 dissolution in the reservoir simulation will more accurately represent ECBM processes. For higher rank coals, which usually have small cleat porosity, lower permeability, a relative permeability curve close to Curve 2, and high adsorption capacity, not accounting for CO_2 dissolution in formation water is still acceptable.

3.2 Scenario 2

The same four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough are used to evaluate the difference between using and not using CO_2 dissolution in the modeling. The results are shown in Table 5.

Table 5. Simulation results for Scenario 2

	Q_{CH4} (m^3/day)	t_b (days)	$V_{t,CH4}$ (10^6 m^3)	$V_{t,CO2}$ (10^6 m^3)	Q_{CH4} (m^3/day)	t_b (days)	$V_{t,CH4}$ (10^6 m^3)	$V_{t,CO2}$ (10^6 m^3)
	With CO_2 dissolution				Without CO_2 dissolution			
Case 1	2210	576	0.616	2.93	2550	406	0.455	2.29
Case 2	2010	893	1.05	4.00	2360	541	0.607	2.77
Case 3	1370	452	0.187	2.37	1830	235	0.096	1.33
Case 4	2320	1083	1.84	4.85	2740	989	1.89	4.68
Case 5	1780	613	0.514	2.93	1980	541	0.465	2.67

For Case 1, the differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 15.4%, 41.9%, 26.1% and 27.9%, respectively. This shows that CO_2 dissolution in the formation waters has a significant impact on gas flow behaviour in the reservoirs. Although the water containing formation has a porosity of 1%, about 2.9% of injected CO_2 before breakthrough is dissolved in the formation waters with 2.4% in the interlayer aquifer. This suggests that CO_2 dissolution modeling must be represented in the modeling when aquifers are in the CO_2 flow path, even though the aquifers have a small porosity.

For Case 2, the aquifer porosity is 2% compared to 1% in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 17.4%, 65.1%, 42.2% and 44.4%, respectively. As expected, with larger aquifer porosity, the impact of CO_2 dissolution is more significant. At CO_2 breakthrough, about 4.3% of the injected CO_2 is dissolved in the formation waters with 3.8% in the interlayer aquifer.

For Case 3, the aquifer thickness is 27 m compared to 9 m in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 33.6%, 92.3%, 48.7% and 78.2%, respectively. As expected, with larger aquifer porosity, the difference of using CO_2 dissolution is larger. At CO_2 breakthrough, about 10.0% of the injected CO_2 is dissolved in the formation waters with 9.5% in the interlayer aquifer. CO_2 dissolution in aquifer is significant so without using CO_2 dissolution will yield huge errors.

For Case 4, the aquifer permeability is 0.05 md compared to 0.5 md in Case 1. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 18.1%, 9.5%, 2.7% and 3.6%, respectively. As expected, with lower permeability, CO_2 flow in the aquifer is limited thus has less impact on the ECBM process in the coal seams.

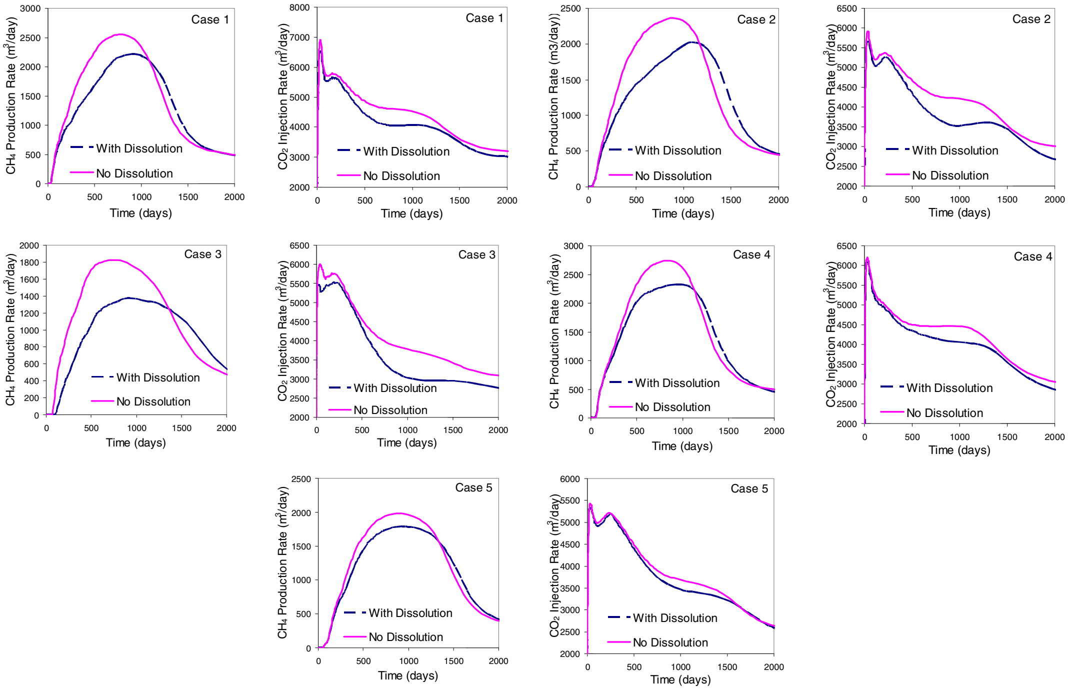

Figure 6. CH_4 production and CO_2 injection rates for difference cases in Scenario 2

For Case 5, the relative permeability used is Curve 2. The differences for the four parameters, CH_4 peak rate, CO_2 breakthrough time, CH_4 produced and CO_2 injected up to CO_2 breakthrough, are 11.2%, 13.3%, 9.5% and 9.7%, respectively. Compared with Case 1, with less difference is observed between using CO_2 dissolution and not using CO_2 dissolution in the modeling.

Figure 6 shows the CH_4 production and CO_2 injection rates for difference cases in Scenario 2. It can be seen from the figure that both rates are significantly different for all the cases. This also suggests that using CO_2 dissolution in this CO_2 injection scenario is essential.

Hence, if the interlayer aquifer has a high porosity, permeability and is thick, in the ECBM process considered in this work, not using CO_2 dissolution in the modeling will yield huge error, since the CO_2 dissolution in the formation waters becomes significant and it has a significant impact on the gas flow behaviour and thus the overall reservoir responses.

4. Conclusions

The work has found that representing CO_2 dissolution in formation water in reservoir simulation improves the accuracy of simulating CO_2 storage for both aquifers and coal seams. The reservoir simulation results for CO_2 injection in a single coal seam to enhance coalbed methane recovery found that including CO_2 dissolution in the calculation leads to significant differences in the model predictions. Although CO_2 dissolution in formation water provides only a minor increase in the total storage capacity, it has other impacts such as on the water saturation which in turn affects the relative gas permeability and thus the overall reservoir pressure and gas flow behaviour. The results also suggest that for CO_2 storage in lower rank coals, which usually have higher porosity and permeability, CO_2 dissolution in the formation water should be considered in order to more accurately describe the CO_2 storage and ECBM behaviour.

For CO_2 injection in coal seams with a low porosity aquifer in-between, including CO_2 dissolution is recommended since the amount of CO_2 dissolved in the aquifer porosity becomes significant and it has significant impacts on the water saturation profile and pressure response in the reservoir leading to significant differences in the simulated gas flow behaviour when compared with the simulation results without dissolution. The impact becomes stronger when the total aquifer formation porosity and permeability are larger.

Acknowledgement

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References

[1] Pruess K. The TOUGH codes - A family of simulation tools for multiphase flow and transport processes in permeable media. Vadose Zone Journal 2004; 3(3): 738-46.

[2] Pruess K, Garcia J, Kovscek T, Oldenburg C, Rutqvist J, Steefel C, Xu T.. Code intercomparison builds confidence in numerical simulation models for geologic disposal Of CO_2. Energy 2004; 29(9-10): 1431-44.

[3] Law DH-S, van der Meer LGH, Gunter WD. Numerical simulator comparison study for enhanced coalbed methane recovery processes, Part I: pure carbon dioxide injection. Presented at the 2002 SPE Gas Technology Symposium, Calgary, Alberta, Canada, paper SPE 75669.

[4] Pan Z, Connell LD. Impact of coal seam as interlayer on CO_2 storage in saline aquifers: A reservoir simulation study. International Journal of Greenhouse Gas Control 2010; in press. Doi:10.1016/j.ijggc.2010.06.012.

[5] Span R, Wagner W. A New Equation of State for Carbon Dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. J. Phys. Chem. Ref. Data 1996; 25(6): 1509-96.

[6] Pruess K, Garcia J, Kovscek T, Oldenburg C, Rutqvist J, Steefel C, Xu T. Intercomparison of numerical simulation codes for geologic disposal of CO_2. LBNL-51812, Contract No. DE-AC03-76SF00098. http://repositories.cdlib.org/lbnl/LBNL-51813. 2002.

[7] Shi J-Q, Durucan S. A model for changes in coalbed permeability during primary and enhanced methane recovery. SPE Reservoir Evaluation & Engineering 2005; 291-9.